# Chapter 8
# Control System

## 8-1. General

*a. Scope*. The control system as discussed in this chapter deals with equipment for the control and protection of apparatus used for power generation, conversion, and transmission. It does not include low-voltage panelboards and industrial control equipment as used with plant auxiliaries. IEEE 1010 and EPRI EL-5036, Volume 10, provide guidelines for planning and designing control systems for hydroelectric power plants.

*b. Control system components*. The control system consists primarily of a computer-based control system, hard-wired logic or programmable logic, indicating and recording instruments, control switches, protective relays, and similar equipment. The greatest part of this equipment should be grouped at one location to facilitate supervision and operation of the main generating units, transmission lines, and station auxiliaries. The grouping of these controls at one location within the confines of the power plant is termed "centralized control."

*c. Start-stop sequence*. Each generator unit control system should be provided with a turbine/generator start-stop sequencing logic using a master relay located at the generator (or unit) switchboard. The starting sequence begins with pre-start checks of the unit, followed by starting unit auxiliaries, and ends with the unit operating under the speed-no-load condition. Manual or automatic synchronizing and closure of the unit breaker can be performed at the local control location. The stopping sequence should provide for four types of unit shutdown: protective relaying, operator's emergency stop switch, mechanical problems, and normal shutdown.

*d. Generator switchboards*. Generator switchboards in larger power plants are located near the controlled generator. The switchboards provide local control of the unit. In smaller power plants, where metal-clad switchgear is used for switching the generator, unit control equipment is located on auxiliary panels of the switchgear line-up. Like the switchboards, the auxiliary panel equipment provides local control of the unit.

*e. Auxiliary equipment control*. Large power plants using high-voltage busing and switching or having an adjacent switchyard as part of the development should have control for this equipment located in the grouping suggested in paragraph 8-1(*b*). Even though the controlled equipment is remote from the plant, the equipment is not "offsite." Offsite control denotes control from a location not resident to the plant, i.e., another plant or a control complex at another location.

*f. Control room location*. In plants with a few units, the control room location with its centralized controls should provide ready access to the governor control cabinets. In plants with ultimately four or more units, the control room should be located near the center of the ultimate plant or at a location allowing ready access to the units and adjacent switchyard. The relative number and lengths of control circuits to the units and to the switchyard is a factor to consider, but is secondary to consideration of operating convenience. The control room should be an elevation above maximum high water, if there is any danger that the plant may be flooded. A decision on the location of the control room should be reached at an early stage of plant design, since many other features of the plant are affected by the control room location. Control location definitions and control modes are further described in IEEE 1010.

*g. Smaller plants*. In smaller power plants, where indoor generator-voltage busing and switching are used, hinged instrument panels on the switchgear cubicles should be used as mounting space for main control equipment. This results in the main group of control equipment being located at the main switchgear location.

## 8-2. Control Equipment

*a. General*. Centralized automatic and manual control equipment should be located in the control room of large power plants. The control console, in conjunction with supervisory control and data acquisition (SCADA) equipment and the status switchboard, enables the control room operator to control the powerhouse operation. Equipment racks housing automatic synchronizing and centralized auxiliary equipment should be located in or adjacent to the control room to facilitate connections with control room equipment. If the plant is controlled from offsite, the plant's SCADA equipment should be located in or adjacent to the control room.

*b. Space allocation*. Space allotted for control equipment, whether in a separate control room or in the main switchgear cubicle area, must be large enough to accommodate the panels required for the ultimate number of generating units and transmission lines. The space requirement, as well as the size and location of openings required in the floor, should be provided to the architectural and structural designers to ensure proper consideration in door, room, and floor slab designs.

*c. Cabinet construction*. Generator switchboard panels and doors should be 1/8-in. thick or No. 11 U.S.S. gauge smooth select steel with angle or channel edges bent to approximately a 1/4-in. radius. Panels should be mounted on sills ready for powerhouse installation in groups as large as can be shipped and moved into the installation area. All equipment on the switchboards should be mounted and wired at the factory, and the boards should be shipped to the powerhouse with all equipment in place.

*d. Equipment arrangement*. The arrangement of equipment on the control switchgear, switchboard, or control console should be carefully planned to achieve simplicity of design and to replicate unit control placements familiar to the intended operating staff. Simplicity of design is a definite aid to operation and tends to reduce operating errors; therefore, the relative position of devices should be logical and uniform. Switchboard and control console design should be patterned after an appropriate example to attain a degree of standardization in the arrangement of indicating instruments and basic control switches. Control switches should be equipped with distinctive handles as shown in Table 8-1. Each item of equipment should be located by consideration of its functions, its relation to other items of equipment, and by its use by the operator.

## 8-3. Turbine Governor

The digital governor electrical control cabinet usually is located adjacent to the generator switchboard separate from the actuator cabinet. The control cabinet contains governor electronic or digital "proportional-integral-derivative" (P-I-D) control components. The actuator cabinet housing the power hydraulics of the governor system is located to minimize the pressure line runs between the turbine servomotors, the actuator, and the governor pressure tank. For smaller capacity governors and smaller plants, governor electronic and hydraulic controls are all located in the governor actuator cabinet. For mechanical considerations of turbine governors, see EM 1110-2-4205.

## 8-4. Large Power Plant Control

*a. General*. Centralized control system equipment is located in the control room and is interconnected to the generator switchboards located near the units. Required control and monitoring of all functions of the hydroelectric power project are provided to the operators. The control console with conventional control devices and monitoring equipment in conjunction with a computer-based data acquisition and control system (DACS), provides control and indication access to individual items of equipment to facilitate operation, supervision, and control. Hard-wired pushbutton switches provide for direct operator manual control of unit start-stop, breaker close (initiating automatic synchronizing), breaker trip, voltage, loading, and gate limit raise-lower. Analog or digital panel meters and indicating lights continuously indicate the status of all main units, breakers, transformers, and lines. The DACS system display monitors and keyboards are available to operator control. The unit controls and instruments supplement or duplicate those on the generator switchboard, and provide the control room operator with the ability to transfer control of any selected unit or group of units to the generator switchboard in case of system trouble. The control console may also provide spillway gate control, fishway control, project communications, and other project equipment control functions when required.

*b. Equipment location*. Arrangement of control and instrument switches and mimic bus should simulate the relative order of interconnections or physical order of the plant arrangement assisting the operator in forming a mental picture of connections. The top of the control console panel should be inclined to provide easier access to the control switches and to improve console visibility. Layouts of console visual display terminals (VDTs) should follow applicable guidelines contained in Chapter 12, "Lighting and Receptacle Systems," to ensure good visual acuity of the displays. Panels of the control console should be arranged for ultimate development, so that the addition of a control panel for another generator or another line will not disturb existing equipment.

*c. Status switchboard*. The status switchboard contains graphic and visual indication, generator load recorders, station total megawatts and megavars recorders, and other required project data displays. The status switchboard should be located for easy observation from the control console. The status switchboard should be a standard modular vertical rack enclosure joined together to form a freestanding, enclosed structure.

*d. Equipment racks*. Equipment racks should be provided for mounting line relays, automatic synchronizing equipment, the common and outside annunciator chassis, auxiliary relays, communication equipment, and transfer trip equipment. The equipment racks should be standard, modular, vertical rack enclosures.

**Table 8-1**
**Typical Plant Control and Instrument Switch Data**

| Switch Function | Contact Type* | No. Pos | Handle Type** | Namplate Marking*** | Escutcheon or Dial Marking Pos-1 | Pos-2 | Pos-3 | Pos-4 | Ind Lights |
|---|---|---|---|---|---|---|---|---|---|
| Exciter AC Voltage Control | A | 3 | BPG | AC VOLT ADJUST | LOWER | - | RAISE | | |
| Excitation Breaker Control | A | 3 | BPG | EXC BKR | TRIP | - | CLOSE | | G,R |
| Exciter DC Voltage Adjust | A | 3 | BPG | DC VOLT ADJUST | LOWER | - | RAISE | | R,A,A,G |
| Generator Breaker Control | A | 3 | BPG | GEN PCB | TRIP | - | CLOSE | | G,R |
| Generator Start/Stop Control | A | 3 | BPG | UNIT START-STOP | STOP | - | START | | G,R |
| Emergency Shutdown (Main Unit) | A | - | RPG | EMERG SHUTDOWN | PULL | AND | TURN | | -- |
| Governor Gate Limit Control | A | 3 | BO | GATE LIMIT | RAISE | - | LOWER | | -- |
| Governor Speed Level Control | A | 3 | BO | SPEED ADJ | RAISE | - | LOWER | | -- |
| Synchronizing (Main Units) | B | 2 | RBO | SYNCH | OFF | ON | | | -- |
| Synchronizing (Switchyard) | B | 3 | RBO | SYNCH | RUN | OFF | INC | | -- |
| Transf, Oil Pump Motor Control | A | 3 | BPG | TRANSF OIL PUMPS | STOP | - | RUN | | G,R |
| Lind M.O. Disc. Switch Control | A | 3 | BPG | LINE SW | OPEN | - | CLOSE | | G,R |
| Aux Bus M.O. Sectionalizing Switch Control | A | 3 | BPG | AUX BUS SW | OPEN | - | CLOSE | | G,R |
| M.O. Disc. Control InterLock | A | 3 | BPG | INTERLOCK | OPEN | - | CLOSE | | -- |
| Ammeter Transfer Switch | B | 4 | BK | GEN AM | A | B | C | OFF | |
| Voltmeter Transfer Switch | B | 4 | BK | GEN VM | OFF | A-B | B-C | C-A | |
| Volt Regulator Transfer Switch | B | 3 | BPG | VOLT REG | OFF | MAN | REG | | W,R |
| Bus Tie PCB Control | A | 3 | BPG | BUS TIE PCB | TRIP | - | CLOSE | | G,R |

*TYPE A - Momentary Spring Return to Neutral
TYPE B - Maintained
** BPG - Black Pistol Grip
RPG - Red Pistol Grip
BO - Black Oval
RBO - Removable Black Oval
BK - Black Knurled
***To suit each application

*e. SCADA equipment*. The SCADA and communication equipment should be located in the general control area.

## 8-5. Small Power Plant Control

*a. General*. Small power plants using medium-voltage metal-clad switchgear for generator control impose different limitations on equipment arrangements than arrangement limitations of generator switchboards for local unit control. This is due to the variety of equipment available with switchgear and, consequently, the different possibilities for locations for major control equipment. As noted in paragraph 8-1*g*, hinged instrument panels on the main switchgear can be used for control equipment. Where space and switchgear construction allow, it is desirable to have hinged instrument panels on the side of the stationary structure opposite the doors for removing the breakers. These panels, however, provide space for only part of the necessary control equipment, and one or more auxiliary switchgear compartments will be required to accommodate the remaining equipment.

*b. Equipment location*. Annunciator window panels, indicating instruments, control switches, and similar equipment should be mounted on the switchgear hinged panels. The hinged panel for each breaker section should be assigned to the generating unit, transmission line, or station service transformer that the breaker serves and only the indicating instruments, control switches, etc., associated with the controlled equipment mounted on the panel. A hinged synchronizing panel should be attached to the end switchgear cubicle.

*c. Additional equipment location*. Protective relays, temperature indicators, load control equipment, and other equipment needed at the control location and not provided for on the switchgear panels should be mounted on the auxiliary switchgear compartments.

*d. SCADA equipment*. Small power plants are frequently unattended and remotely controlled from an off-site location using SCADA equipment. The SCADA and communication equipment should be located in the general control area.

## 8-6. Protective Relays

*a. General*. The following discussion on protective relays includes those devices which detect electrical faults or abnormal operating conditions and trip circuit breakers to isolate equipment in trouble or notify the operator through alarm devices that corrective action is required. The application of relays must be coordinated with the partitioning of the electrical system by circuit breakers, so the least amount of equipment is removed from operation following a fault, preserving the integrity of the balance of the plant's electrical system.

(1) Generally, the power transmitting agency protection engineer will coordinate with the Corps of Engineers protection engineer to recommend the functional requirements of the overlapping zones of protection for the main transformers and high voltage bus and lines. The Corps of Engineers protection engineer will determine the protection required for the station service generators and transformers, main unit generators, main transformers, and powerhouse bus.

(2) Electromechanical protective relays, individual solid state protective relays, multi-function protective relays, or some combination of these may be approved as appropriate for the requirements. Traditional electromechanical protective relays offer long life but may malfunction when required to operate, while many less popular designs are no longer manufactured. Individual solid state protective relays and/or multi-function protective relays offer a single solution for many applications plus continuous self diagnostics to alarm when unable to function as required. Multi-function protective relays may be cost-competitive for generator and line protection when many individual relays would be required. When multi-function relays are selected, limited additional backup relays should be considered based upon safety, the cost of equipment lost or damaged, repairs, and the energy lost during the outage or repairs if appropriate.

(3) When the protection engineer determines that redundancy is required, a backup protective relay with a different design and algorithm should be provided for reliability and security. Fully redundant protection is rarely justified even with multi-function relay applications. Generators, main transformers, and the high voltage bus are normally protected with independent differential relays.

(4) When the protective relays have been approved, the protection engineer will provide or approve the settings required for the application.

*b. Main generators*.

(1) The general principles of relaying practices for the generator and its excitation system are discussed in IEEE standards C37.101, C37.102, and C37.106.

Unless otherwise stated, recommendations contained in the above guides apply to either attended or unattended stations.

(2) Differential relays of the high speed, percentage differential type are usually provided to protect the stator windings of generators rated above 1500 *kVA*.

(3) A high-impedance ground using a resistance-loaded distribution transformer scheme is generally used, thereby limiting generator primary ground fault current to less than 25 A. A generator ground, AC overvoltage relay with a third harmonic filter is connected across the grounding impedance to sense zero-sequence voltage. If the generator is sharing a GSU transformer with another unit, a timed sequential ground relay operation to isolate and locate generator and delta bus grounds should be provided.

(4) Out-of-step relays are usually provided to protect generators connected to a 500-*kV* power system, because the complexity of a modern EHV power system sometimes leads to severe system frequency swings, which cause generators to go out of step. The generator out-of-step relays should incorporate an offset mho and angle impedance relay system which can detect an out-of-step condition when the swing locus passes through the generator or its transformer.

(5) Frequency relays, and under- and over-frequency protection, are not required for hydraulic-turbine-driven generators.

(6) Temperature relays are provided for thrust and guide bearings as backup for resistance temperature detectors and indicating thermometers with alarms. The relays are set to operate at about 105° C and are connected to shut down the unit. Shutdown at 105° C will not save the babbitt on the bearing but will prevent further damage to the machine.

*c. Generator breakers*.

(1) Most breaker failure relaying schemes operate on high phase or ground currents. When a trip signal is applied to the breaker, the breaker should open and current flow should cease within the breaker interrupting time. The breaker failure relay is usually applied to operate lockout relays to trip backup breakers after a time delay based on the assumption the breaker has failed if current flow continues after the breaker trip circuit has been energized. These schemes do not provide adequate protection if breaker failure occurs while current is near zero immediately following synchronizing.

(2) Another scheme uses a breaker auxiliary contact to detect breaker failure with fault detectors for phase current balance, reverse power, and overcurrent relays. Protective relay contact closing or operation of the breaker control switch to the trip position energizes a timing relay. If the breaker auxiliary contact does not close within the breaker interrupting time, the timing relay will close its contacts, enabling the phase current balance, reverse power, and overcurrent relays to perform the required trip functions.

(3) Some breaker control systems monitor the breaker trip coil using a high resistance coil relay connected in series with the trip coil. A time delay relay is required to allow the breaker to open during normal tripping without initiating an alarm.

(4) Provision should be made to trip generator breakers when there is a loss of the breaker trip circuit DC control power or complete loss of DC for the entire plant. A stored energy capacitor trip device can be used to trip the breaker in case of a loss of control power.

*d. Transformer protection*.

(1) Transformers or transformer banks over 1500 *kVA* should be protected with high-speed percentage-type differential relays. The basic principles involved in transformer protection are discussed in IEEE C37.91.

(2) Separate differential relay protection for generators and transformers should be provided even on unit installations without a generator circuit breaker. The relays applicable for generators can be set for much closer current balance than transformer differential relays.

(3) Auto transformers can be treated as three-winding transformers and protected with suitable high-speed differential relays. The tertiary winding of an auto-transformer usually has a much lower *kVA* rating than the other windings. The current transformer ratios should be based on voltage ratios of the respective windings and all windings considered to have the same (highest) *kVA* rating.

(4) Thermal relays supplement resistance temperature detectors and thermometers with alarm contacts. The relays are set to operate when the transformer temperature reaches a point too high for safe operation, and are

connected to trip breakers unloading the transformers. These relays are important for forced-oil water-cooled transformers which may not have any capacity rating without cooling water.

*e. Bus protection.*

(1) High-voltage switchyard buses can be protected with bus protection, but the necessity and type of bus protection depends on factors including bus configuration, relay input sources, and importance of the switchyard in the transmission system. Application of bus protection should be coordinated with the PMA or utility operating agency. The basic principles of bus protection operation are discussed in IEEE C37.97.

(2) Large power plants with a complex station service system configuration should be provided with station service switchgear bus differential relay protection.

(3) A ground relay should be provided on the delta-connected buses of the station service switchgear. A voltage relay, connected to the broken-delta potential transformer secondary windings, is usually provided to detect grounds. A loading resistor may be placed across the broken delta to prevent possible ferroresonance. The ground detector usually provides only an alarm indication.

*f. Feeder protection.* Feeder circuits that operate at main generator voltage and 4160-V station service feeders should be protected with overcurrent relays having instantaneous trip units and a ground relay. The setting of the ground relay should be coordinated with the setting of the generator ground relay to prevent shutdown of a generator due to a grounded feeder.

*g. Transmission line protection.* Relays for the protection of transmission lines should be selected on the basis of dependability of operation, selectivity required for coordination with existing relays on the interconnected system, speed of operation required to maintain system stability, coordinating characteristics with relays on the other end of the line, and the PMA or utility system operating requirements. The basic principles of relaying practices are discussed in IEEE C37.95.

*h. Shutdown relays.* The shutdown lockout relays stop the unit by operating shutdown equipment and tripping circuit breakers. The lockout relay operations are usually divided into two groups. A generator electrical lockout relay, 86GX, is initiated by protective relaying or the operator's emergency trip switch. The generator mechanical lockout relay, 86GM, is triggered by mechanical troubles, such as bearing high temperatures or low oil pressure. The unit shutdown sequence is described in IEEE 1010.

## 8-7. Automatic Generation Control (AGC)

For computer-based control systems, unit load can be controlled in accordance with an error signal developed by digital computers periodically sampling real power flow over the tie line, line frequency, and generator power output. These analog signals are continuously monitored at the load dispatch control center to obtain the plant generation control error. The control error digital quantity is transmitted via telemetry to each plant and allocated to the units by the computer-based plant control system. AGC action by the plant control system converts the raise/lower megawatt signal into a timed relay contact closure to the governor. The governor produces a wicket gate open/close movement to change the generator output power. Other modes of operation include set point control, regulating, base loaded, ramped control, manual control, and others relative to the nature of the project and operating philosophy. Coordination of the engineering planning of the AGC with the marketing agency should begin at an early stage.